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Balancing the Baryon Budget: The fraction of the IGM due to Galaxy Mergers

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ABSTRACT

Observations indicate that roughly 60% of the baryons may exist in a Warm-Hot Intergalactic Medium (WHIM) at low redshifts. Following up on previous results showing that gas is released through galaxy mergers, we use a semi-analytic technique to estimate the fraction of gas mass lost from haloes solely due to mergers. We find that up to $\sim$ 25% of the gas in a halo can unbind over the course of galaxy assembly. This process does not act preferentially on smaller mass haloes; bigger haloes *always* release larger amounts of gas in a given volume of the Universe. However, if we include multi-phase gas accretion onto haloes, we find that only a few percent is unbound. We conclude that either non-gravitational processes may be in play to heat up the gas in the galaxies prior to unbinding by mergers or most of the baryons in the WHIM have never fallen into virialised dark matter haloes. We present a budget for stocking the WHIM compiled from recent work.

Key words:
galaxies: evolution - galaxies: haloes - galaxies: interactions - intergalactic medium - methods: numerical - cosmology: large-scale structure

1 INTRODUCTION

The baryon budget shows significant evolution from $z \sim 3$, and results in an apparent baryon deficit today (Fukugita et al. 1998; Fukugita & Peebles 2004). At high redshift, most of the baryonic mass is in the Ly-α forest (Fukugita et al. 1998; Fukugita & Peebles 2004), while at low redshifts over half of the baryons are as yet undetected. The consensus is that the majority of the 'missing' baryons are actually in regions of low overdensity, $\delta\rho/\rho \sim 10-100$ (e.g Cen & Ostriker 1999; Davé et al. 1999, 2001; Kang et al. 2005; Cen & Ostriker 2006; Dolag et al. 2006; Davé & Oppenheimer 2007) with temperatures in the range 10^5-10^7 K – commonly referred to as the Warm-Hot Intergalactic Medium (WHIM).

The immediate question is: how is this WHIM produced ? Some form of mass and energy injection is essential to create this hot reservoir of gas; this form of feedback must both regulate the gas in galaxies and the metal content of the Intergalactic Medium (IGM). There has been much numerical work to incorporate various feedback mechanisms in an attempt to solve this puzzle (e.g., Cen & Ostriker 1999; Nath & Silk 2001; Davé et al. 2001; Kang et al. 2005; Cen & Ostriker 2006; Davé & Oppenheimer 2007, and references therein). Cosmological simulations seem to suggest that gravitational collapse during galaxy formation can produce and maintain the majority of the WHIM at 10^5-10^7 K (Cen & Ostriker 1999; Davé et al. 1999; Cen & Ostriker 2006; Croft et al. 2001; Davé & Oppenheimer 2007). Supernova feedback provides another avenue to generate the WHIM; for star bursts of 100 $M_\odot$ per year, as much as 20% of the hot gas in a Milky Way mass galaxy can be unbound (Scannapieco et al. 2006; Kobayashi et al. 2007). However, SNe feedback may be a self regulating process, in that a starburst also heats the remaining gas and may damp the star formation rate, which in turn would reduce the fraction of unbound gas (e.g. Scannapieco et al. 2008). Combining these effects, it is commonly thought that galaxies with host halo mass $\gtrsim 10^{11}$ M$_\odot$ lose $\lesssim$ 10% of their gas through SN feedback, while low mass haloes may be entirely depleted of gas by this mechanism(Yepes et al. 1997; Mac Low & Ferrara 1999; Efstathiou 2000; Scannapieco et al. 2006). A third possibility is that the radiation from an accreting supermassive black hole could power large-scale winds to blow mass out of the galaxy (see Scannapieco & Oh 2004; Murray et al. 2005; Hopkins et al. 2005a,b, 2006; Croton et al. 2006; Sijacki et al. 2007). For a fixed amount of energy, all the non-gravitational feedback mechanisms are more effective in

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low mass galaxies due to their shallower potential. However, observations suggest that low-mass galaxies are in general more gas-rich and are less likely to have suffered a gas blowout (Kannappan 2004; Geha et al. 2006).

In Sinha & Holley-Bockelmann (2009, hereafter, SH09), we show that hot gas is driven into the IGM by galaxy mergers. The amount of hot halo gas lost depends strongly on the energy of the merger; it is possible for low mass galaxies to retain their gas in this scenario during low-speed or distant encounters. However, SH09 only estimated the mass lost during a single merger. When all the mergers in the Universe are considered, this could heat and drive a significant portion of the total baryon budget into the WHIM. In principle, this process could join AGN and star formation feedback as a way to populate the WHIM, and we find that this method operates preferentially in *more* massive haloes. To estimate the total fraction of gas released by mergers, we construct a series of analytic halo merger trees using a publicly available[1]semi-analytic Extended Press-Schechter (EPS) code (Parkinson et al. 2008).

In Section 2 we describe the theory of halo merger trees, in Section 3 we outline the experiments designed to track the gas ejected via galaxy mergers, in Section 4 we present the results for the halo gas ejected by this process and Section 5 contains the discussion.

2 CONSTRUCTING MERGER-TREES

Observations reveal that we live in low-density, Λ-dominated flat Universe (Riess et al. 1998; Perlmutter et al. 1997; Spergel et al. 2007; Komatsu et al. 2009). In such a Universe, haloes form hierarchically, with smaller haloes forming early on and merging into larger structures at later times. This process of halo formation is dictated by gravitational processes, and an analytic formalism yields the number density of haloes as a function of mass and redshift (Press & Schechter 1974). However, this does not constrain the merger rates for any given halo as a function of redshift. To this end, the Press-Schechter formalism has been extended to calculate a merger history of a halo in the form of a binary merger tree (Lacey & Cole 1993; Bower 1991; Bond et al. 1991). These merger trees are computationally much less expensive than an N-body simulation, and are widely used to explore and constrain theories of galaxy evolution, black hole growth, etc. We use the technique here to estimate the gas lost to the WHIM via galaxy mergers.

In the EPS model of Parkinson et al. (2008), the conditional mass function $f(M_1|M_2)$ gives the fraction of mass from a halo with mass M_2 at a redshift z_2 that was contained in a progenitor halo of mass M_1 at a previous redshift z_1:

$$f(M_1|M_2)\,d\ln M_1 = \sqrt{\frac{2}{\pi}}\,\frac{\sigma_1^2(\delta_1-\delta_2)}{[\sigma_1^2-\sigma_2^2]^{3/2}} \times \exp\left[-\frac{1}{2}\frac{(\delta_1-\delta_2)^2}{(\sigma_1^2-\sigma_2^2)}\right]\left|\frac{d\ln\sigma}{d\ln M_1}\right| d\ln M_1\,, \tag{1}$$

where δ_1 and δ_2 represent linear overdensities for collapse at redshifts z_1 and z_2 and $\sigma \equiv \sigma(M)$. The derivative of this equation under the limit $z_1 \to z_2$ yields the number N of progenitors of mass M_1 that make up a halo of mass M_2 for a small step in redshift space of $\mathrm{d}z_1$. This is written as:

$$\frac{dN}{dM_1} = \frac{1}{M_1}\,\frac{df(M_1|M_2)}{dz_1}\,\frac{M_2}{M_1}dz_1 \qquad (M_1 < M_2). \tag{2}$$

Specifying a minimum mass resolution M_{res} allows us to compute the mean number of progenitors N_P with mass M_1 in a mass range $M_{\mathrm{res}} < M_1 < M_2/2$ via the following equation:

$$N_P = \int_{M_{\mathrm{res}}}^{M_2/2} \frac{dN}{dM_1}\,dM_1\,. \tag{3}$$

The mass fraction F of the final halo M_2 that is accreted below M_{res} can be estimated from:

$$F = \int_0^{M_{\mathrm{res}}} \frac{dN}{dM_1}\,\frac{M_1}{M_2}\,dM_1\,. \tag{4}$$

A binary merger tree can then be constructed given M_2 and z_2. We used this technique to construct a set of twelve merger-trees, which we outline in Section 3. We have assumed a flat ΛCDM cosmology with $\Omega_{\mathrm{b}} = 0.044$, $\Omega_{\mathrm{dm}} = 0.214$, $\Omega_\Lambda = 0.742$, $\sigma_8 = 0.796$ and $h = 0.719$, consistent with the WMAP 5-year cosmology parameters (Komatsu et al. 2009).

3 METHOD

As shown in SH09, the amount of gas[2]released by a galaxy merger depends on the mass ratio and the original gas content of the haloes. To incorporate this effect within a merger tree we take the following approach: we seed each halo with a gas fraction (f_{seed}) and assume a galaxy merger with a mass ratio greater than η_{min} unbinds a fraction of this gas (f_{unb}). We also assume that as the halo grows by diffuse accretion from the IGM, it also accretes gas at the universal gas fraction, increasing the halo gas content. Recent simulations (see Kereš et al. 2005, 2009; Dekel et al. 2009) show that gas does not necessarily heat up to the halo virial temperatures; the majority of the haloes at low-z are only accreting cold gas. To estimate the effect of this multiphase accretion models, we divided the halo gas mass into hot and cold components in accordance with Figure 3 of Kereš et al. (2009). After this partitioning, we follow the same procedure, except now we only unbind gas from the hot gas component. Table 1 outlines the parameters for the twelve experiments.

We designed these twelve experiments to bracket the likely effect that galaxy mergers have on populating the WHIM. A reasonable upper limit is set by allowing even minor mergers ($\eta_{\mathrm{min}} = 0.1$) to unbind a fixed fraction ($f_{\mathrm{unb}} = 0.1$) of the progenitor gas mass (run Minor1). Our lower limit is set by seeding only the massive haloes ($M_{\mathrm{halo}} \geqslant M_{\mathrm{min}} = 10^{10}\,\mathrm{M}_\odot$) with gas at the universal gas fraction and allowing only major mergers ($\eta = 0.3$) to release gas (run Major5). SH09 found that roughly equal-mass mergers can release up to 20% of their initial gas mass, and since the merger rate (per halo per redshift) is relatively flat from $0.3 < \eta < 1.0$ (see Fig. 8 in Fakhouri & Ma 2008), we argue that $\eta_{\mathrm{min}} = 0.3$, $f_{\mathrm{unb}} = 0.1$ is a good average scenario.

[1] `http://star-www.dur.ac.uk/~cole/merger_trees/`

[2] Since we do not model star formation in our semi-analytic approach, we will use the terms gas and baryons interchangeably.

Table 1. The initial parameters for the twelve merger trees. Column 1 is the minimum merger ratio for gas to get ejected from haloes, column 3 is the fraction of the halo mass used to seed newly-appeared haloes (equal to Ω_b/Ω_{dm} for all experiments other than Major3 and Minor3), column 4 is the fraction of the halo gas that unbinds during a merger, column 5 is the minimum halo mass that can retain gas and column 6 shows the entire mass range of haloes for which merger trees were made.

$\eta_{\rm min}$	**Run**	$\mathbf{f_{seed}}$	$\mathbf{f_{unb}}$	$\mathbf{M_{min}}$	**Mass range**
[-]	[-]	[-]	[%]	[log $M_\odot$]	[log $M_\odot$]
0.33	Major1	0.21	10.0	-	8.0 - 13.0
	Major2	0.21	random	-	8.0 - 13.0
	Major3	random	10.0	-	8.0 - 13.0
	Major4	0.21	10.0	-	10.0 - 13.0
	Major5	0.21	10.0	10.0	10.0 - 13.0
	Major-Keres	0.21	10.0	-	8.0 - 13.0
0.10	Minor1	0.21	10.0	-	8.0 - 13.0
	Minor2	0.21	random	-	8.0 - 13.0
	Minor3	random	10.0	-	8.0 - 13.0
	Minor4	0.21	10.0	-	10.0 - 13.0
	Minor5	0.21	10.0	10.0	10.0 - 13.0
	Minor-Keres	0.21	10.0	-	8.0 - 13.0

Haloes more massive than $10^{13}\,M_\odot$, representing groups or clusters of galaxies, can not be faithfully modelled using this binary galaxy merger mechanism and have been left out.

The input parameters are the final halo mass, M_2, the initial redshift, $z_1 = 10$ and the mass resolution, $M_{\rm res}$. We explore a range of final halo masses from $M_2 = 10^8 - 10^{13}\,M_\odot$. We use 100 logarithmically spaced mass bins to create a merger tree for a specific M_2 at the present epoch. To account for cosmic variance, we run 100 realisations of a fixed halo mass. Thus, overall we create 100 present day halo samples with 100 realisations for a fair sample of possible hierarchical merger histories of structure in the Universe. For each merger tree, we set $M_{\rm res} = M_2 \times 10^{-5}$. For $10^{11}\,M_\odot$ haloes, this value of $M_{\rm res}$ is comparable to the mass of an individual dark matter particle in our numerical simulations (SH09). We tested the effect of changing $M_{\rm res}$, z_1 and the number of redshift levels and found that our choices produce convergent results for the estimation of the unbound gas.

With these merger histories, we follow all mergers from $z = 10$ to $z = 0$ that lead to a halo of mass M_2, and eject a fraction of gas from the mergers with mass ratios greater than $\eta_{\rm min}$. The cumulative sum of the unbound gas produces the total gas released in assembling a particular halo. This yields the fractional gas lost by $z = 0$ on a *per halo* basis. We repeat this process for 100 realisations, which provides the variance in the gas lost. We can find the total gas released in generating all haloes in the Universe by convolving with the co-moving number density of those haloes at $z = 0$(Warren et al. 2006). Summing over the final halo masses yields the effect of halo assembly on populating the WHIM.

4 RESULTS

Figure 1 shows the redshift evolution of the cumulative gas mass lost from all haloes in a co-moving Mpc^3 volume for the run Major1. To generate Figure 1, we first take the mean of 100 realisations for the unbound gas mass in each redshift step for each halo. This unbound gas mass is added up along the redshift track to yield the cumulative mass at each redshift step and then multiplied by the co-moving number density of that particular halo at $z = 0$. This is the cumulative co-moving density of the unbound gas for one halo mass. Repeating this process for the 100 final halo masses yields the individual tracks spanning the x-axis. Figure 1 shows that the most massive haloes unbind the most gas at all redshifts, in spite of their lower number densities. For example, the current number density in a co-moving Mpc^3 of a $10^{13}\,M_\odot$ halo is $\sim 10^6$ times smaller than for a $10^8\,M_\odot$ halo; so the mass-density of the $10^8\,M_\odot$ halo is an order of magnitude larger than the $10^{13}\,M_\odot$ halo. This biasing towards higher mass is explained by the hierarchical assembly of haloes – more massive objects today undergo many more mergers in the past[3].

Figure 2 shows the redshift evolution of the unbound gas mass over the total baryon mass in all the haloes considered in the merger tree. We find that 9% and 24% of the baryons can be ejected by mergers for the Major1 and Minor1 runs respectively. The mass range of $10^{10} - 10^{13}\,M_\odot$ and $10^8 - 10^{13}\,M_\odot$ contain 39% and 52% of the total collapsed mass in the Universe respectively. Thus, the IGM pollution caused by the mergers presented in this paper can only reflect the history of at most half the total matter. If we assume that the same pattern holds true globally, then the fractions presented here (Figure 2) can be interpreted as normalised by the total baryonic matter density of the Universe. Notice that the fraction of gas lost increases more rapidly with redshift for $\eta_{\rm min} = 0.1$ – this is because 10:1 mergers occur more frequently than 3:1 (e.g., Fakhouri & Ma 2008; Genel et al. 2009).

We can interpret Figure 2 in the following way: in the Major1 run, the convergence to 10% of the universal gas mass is tantamount to saying that the average halo undergoes one major merger in a Hubble time, since we set major mergers to release 10% of the gas mass. Likewise, the convergence of the Minor1 run can be understood by noting that minor mergers ($\eta > 0.1$) are $2-3$ times more frequent than major mergers ($\eta > 0.3$, Fakhouri & Ma (see bottom panel of Fig. 8 in 2008)). Thus, the overall unbound density converges to $\sim 20-30\%$ for the Minor1 run.

In run Major-Keres with multiphase accretion, we find that only $\sim 2\%$ of the gas can be released due to mergers. Since the simulations of SH09 only included hot gas, we chose to unbind only from that phase. In the multiphase scenario, too much gas is in the cold phase and hence, can not be released during mergers. Even adding a mechanism to heat cold gas by major mergers (Eqn. 4 Cox et al. 2004) does not convert enough cold gas into a hot phase to be unbound later. If the haloes are only accreting cold gas and this gas can not be unbound from the haloes before heating

[3] There may be an additional effect from the higher gravitational potential energy ($\propto v_{\rm circ}^2$) involved during mergers of massive galaxies (see Johansson et al. 2009).

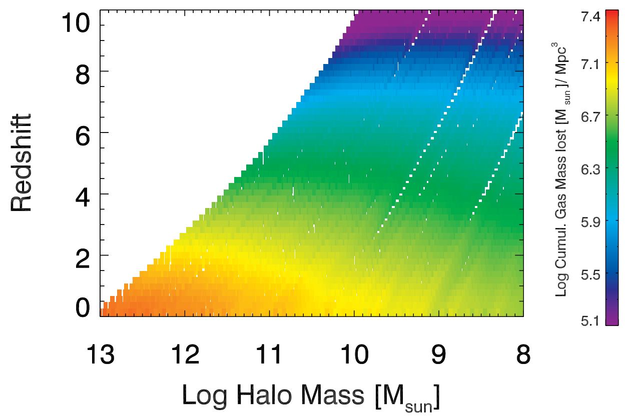

Figure 1. The cumulative gas mass lost from haloes by mergers in a co-moving Mpc^3 volume as a function of halo mass and redshift for Major1. Despite their larger number density, smaller haloes systematically lose less mass than the bigger haloes. The gas mass lost is obtained by taking a mean of 100 realisations. The pixels reflect the bin size in mass and redshift. This figure is summing the unbound gas mass along redshift and multiplying by the co-moving number density of the corresponding haloes at $z = 0$.

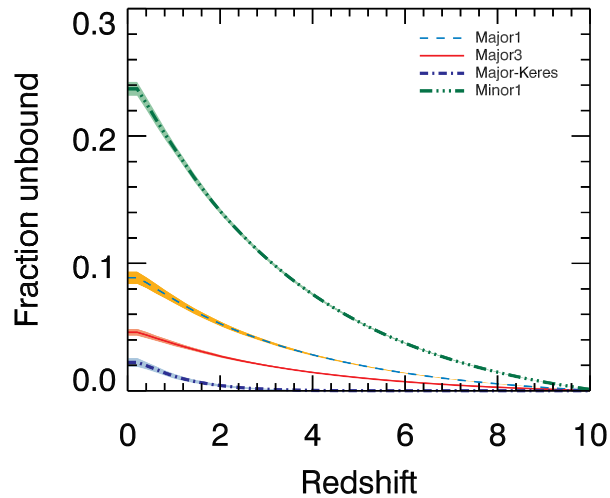

Figure 2. The evolution with redshift of the gas mass lost as a fraction of baryon density in the Universe baryon content in the merger trees assuming universal gas fraction. If we assume that the trend holds globally, then the Y-axis can be thought to be normalised by $\rho_{\rm b}$. The shaded region shows the 1-σ deviation at each redshift from 100 realisations.

it first, then the gas currently populating the WHIM may not have ever fallen into virialised haloes.

In a given merger tree, a fraction of unbound gas is released by mergers between small haloes. To isolate the WHIM fraction (Table 2, Column 5)created during the assembly of *only* the massive galaxies, we run two sets of merger trees with a lower mass limit of $10^{10}\,{\rm M}_\odot$. Table 2 shows that most of the unbound gas that is released comes during the formation of the massive galaxies. In particular, Major4, with only the massive haloes, produces nearly all of the unbound gas produced in the Major1 run.

Although small haloes merging with massive haloes do not eject any gas, these minor accretion events increase the gas content of the remnant. This could potentially increase the amount of gas released by massive haloes in future mergers. However, if processes like SN feedback evacuate the gas from low mass haloes, these low mass haloes can not increase the gas content of the massive haloes. To mimic this effect, we run two sets of merger trees with a lower mass limit of $10^{10}\,{\rm M}_\odot$ and only allow haloes larger than $M_{\rm min}$ to contain gas. In this scenario (Major5 and Minor5), all small haloes are completely devoid of gas and therefore do not contribute to the gas mass of the big haloes. With this constraint, we find a WHIM fraction of $\sim 3\%$ and 8% for $\eta_{\rm min} = 0.3$ and 0.1 respectively.

Table 2. A census of the unbound gas at $z = 0$ produced by galaxy mergers. Column 2 is the mass of unbound gas in a co-moving Mpc^3, column 3 is the ratio of unbound gas mass and the expected universal gas content ($M_{\rm halo} \times \Omega_{\rm b}/\Omega_{\rm dm}$). Column 4 is the ratio of the mean unbound gas in a co-moving Mpc^3 to the mean gas mass left the haloes. Column 5 shows the fraction of the WHIM generated; we assume that the WHIM contains 60% of all the baryons. The gas mass in a co-moving Mpc^3 volume for the haloes considered here is $7.6 \times 10^9\,{\rm M}_\odot$.

Run	$\mathbf{M_{gas,unb}}$	$\frac{<\mathbf{M_{unb,gas}}>}{<\mathbf{M_{gas,univ}}>}$	$\frac{<\mathbf{M_{unb,gas}}>}{<\mathbf{M_{gas,gal}}>}$	$\mathbf{f_{WHIM}}$
[-]	$[\mathbf{10^8 M_\odot/Mpc^3}]$	[-]	[-]	[-]
Major1	6.7 ± 0.4	0.09	0.10	0.15
Major2	3.5 ± 0.2	0.05	0.05	0.08
Major3	5.7 ± 0.3	0.07	0.09	0.12
Major4	5.0 ± 0.3	0.09	0.10	0.15
Major5	1.0 ± 0.1	0.02	0.04	0.03
Major-Keres	1.7 ± 0.3	0.02	0.03	0.03
Minor1	17.9 ± 0.4	0.24	0.32	0.39
Minor2	9.7 ± 0.3	0.13	0.15	0.21
Minor3	15.2 ± 0.4	0.20	0.29	0.33
Minor4	13.4 ± 0.4	0.24	0.32	0.40
Minor5	2.9 ± 0.1	0.05	0.13	0.08
Minor-Keres	3.8 ± 0.3	0.03	0.06	0.06

5 DISCUSSION

In this paper we show that a significant portion of the WHIM can be generated by gas ejected from galaxies during mergers. Our semi-analytic prescription shows that up to $\sim 25\%$ of the gas (assuming universal gas fraction) in haloes of mass $10^8 - 10^{13}\,{\rm M}_\odot$ can be ejected by mergers. Given an observed gas mass at $z = 0$, it is possible to infer the typical gas mass that was unbound from assembling that halo (column 4, Table 2) For comparison with SN feedback, a quiescent Milky-Way type halo with star formation rate of 1-10 ${\rm M}_\odot{\rm yr}^{-1}$ would unbind $\leqslant 2\%$ of the gas content (Scannapieco et al. 2008). We also find that multiphase gas accretion drastically reduces the amount of unbound gas from mergers, down to a few percent of the gas mass. In contrast with previous numerical work involving non-gravitational feedback, where the effects of mass loss are severe in smaller haloes, this merger mechanism unbinds gas preferentially from massive haloes. There is no selective unbinding of gas from dwarf

galaxies, in line with observational evidence suggesting that dwarf galaxies are more gas-rich and therefore may not have suffered a gas blow-out (Kannappan 2004; Geha et al. 2006).

This form of *gravitational feedback* may even play a larger role in regulating the stellar mass function: Kereš et al. (2009) show that simulated galaxies exhibit a discrepancy with the observed stellar mass function (Bell et al. 2003) for both high and the low mass galaxies. They conjecture that the key to solving this discrepancy is through a feedback mechanism that works for halos $\gtrsim 10^{12}\,\mathrm{M}_{\odot}$ – akin to our scenario. If the merger-ejection process is very efficient, then the current day haloes may be very gas-poor. It is conceivable that the current stellar mass *and* the gas fraction of a galaxy constrains the mean stellar mass and gas content of the galaxies of the past.

Overall, we find that for our most reasonable scenario, $\sim 15\%$ of the WHIM can be generated through galaxy mergers. If previous work on large-scale gravitational shocks proves correct (Cen & Ostriker 1999; Davé et al. 2001), $\sim 66\%$ of the WHIM can be attributed to gas that may have never fallen into a halo. In addition, recent studies have shown that roughly 20% can be produced via non-gravitational feedback, such as SNe and AGN (e.g., Cen & Ostriker 2006). Therefore, with these three mechanisms to populate the WHIM, it may well be true that the baryon budget is balanced.

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